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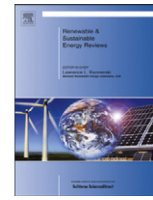

A comparative analysis of wind power density prediction methods for Çanakkale, Intepe region, Turkey

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ABSTRACT

Wind is an environmentally natural and a renewable source of energy. In most parts of the world, wind energy has been utilized as an energy source. In some developed countries, particularly in Europe, the global climate change issue has been the main cause of the wind energy developments. In parallel to these developments, the importance dedicated to the renewable energies has risen in recent years in Turkey; and the number of renewable energy operated power plants has gradually increased as a result. Determination of the potential has the priority for the energy generation from wind power studies. The present study attempts to review and discuss the status and potential of Çanakkale—Intepe region in Turkey with a focus on wind energy. Wind energy resource assessment was carried out by using WAsP software. The average wind speed data and the potential wind energy generation are determined using dominant wind directions, speeds, and the frequency distribution in between 2009 and 2010 for Çanakkale—Intepe region. The results show that the total average of wind speed for the year is 4.26 m/s and average power density is 115.5 W/m^2. Besides wind speed frequencies has been compared with the Weibull, Rayleigh and Normal distribution functions. As a result the Wiebull distribution suits and verifies the actual values. According to the analysis the most frequent wind speed is notably high. The obtained data are classified based on the measurement elevations and the energy potentials were determined using reliable meteorological measurements. Some practical data and considerations given in this study can be used by a company keen to invest in the wind potential in Intepe. A possible wind farm design was performed in the mentioned region.

Contents

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Nomenclature

$f_w(v)$	Weibull distribution function
k	Weibull shape factor
c	Wiebull scale parameter
v	wind speed
$\overline{v}$	mean wind speed
h	hub height
α	wind shear coefficient
G_i	sensitivity coefficients
X_i	measurement errors
Γ	gamma function
σ	standard deviation
$f_R(v)$	density function of the Rayleigh distribution
P_m	wind power density
ρ	standard air density
P_{mv}	average wind power density
A	average wind speed
U	figure parameter
E	energy density
f	frequency

Table 1
Resources used for electrical energy production in Turkey (2012) [10].

Source	Installed power (MW)
Natural gas	16,042.5
Lignite + hard coal	12,395
Coal	2081
Geothermal	162
Liquid gas	1798
Wind	2261
Hydro	19,620
Others (Diesel + LPG + LNG + Naptha)	2712
Total	57,072

1. Introduction

The development of the Turkish industry carried with it the demand for energy. The current energy resources are insufficient to meet this energy demand. Especially the shortage of the fossil fuels and the increase of their cost during the last few years have raised the attention towards the alternative energy resources. As the energy demand increases both for the industry and everyday life, the conventional energy resources become scarce very rapidly. According to the TEIAS's (Turkey Electricity Transmission Company) statistical data, the installed power of Turkey was 5118.7 MW in 1980, and 57,072 MW at the end of 2012. According to TEIAS's projection, installed power levels will be at 78,175 MW in

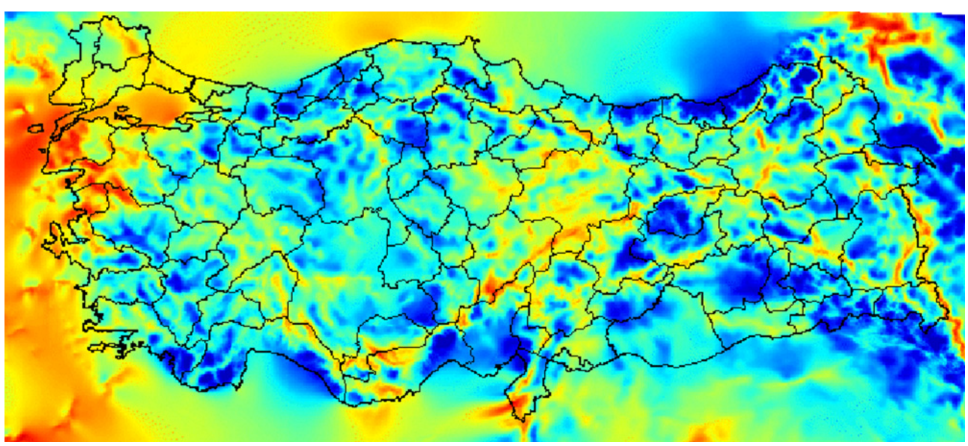

Fig. 1. Average wind speed map of Turkey (30 m) [11].

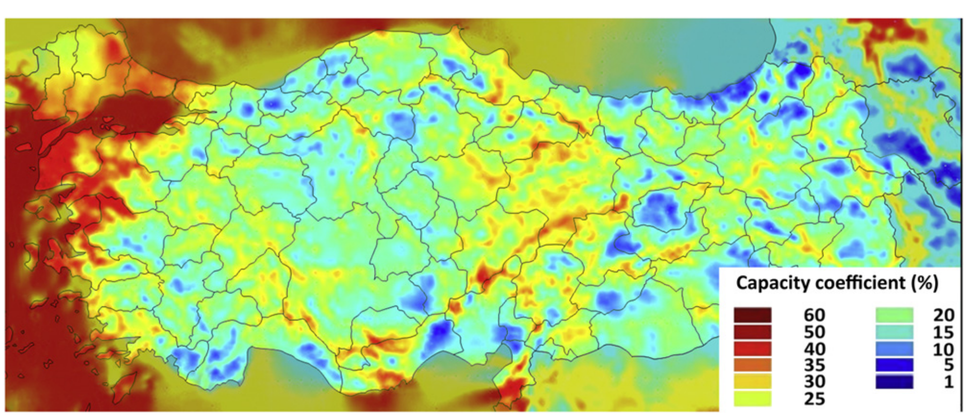

Fig. 2. Average capacity coefficient in Turkey (30 m) [11].

2016. The increase of the energy demand and the decrease of the energy resources force Turkey to increase energy importation. According to the statistical data of the Ministry of Energy and Natural Resources, Turkey imports 914 GWh of electrical energy as in 2012, while the gross energy demand was 239,200 GWh in the same year [1]. As it is seen from Table 1, Turkey obtains 60% of its installed power from fossil fuels.

Environmental effects of the fossil fuels have raised the need for clean and renewable energy resources. Wind energy is a renewable energy source that had a higher growth in the last few decades and can be considered as a hope in the future based on clean and sustainable energy [2,3]. Turkey has geographical properties that provide easy access to renewable energy sources such as wind, solar and geothermal. Several wind energy feasibility and characteristics analyses have been made over the last decade all over the world and Turkey. Keyhani et al. carried out a study using the statistical data of eleven years "wind speed measurements" of the capital of Iran, Tehran, to find out the wind energy potential; however the study did not involve different analysis methods [4]. Lima and Filho investigated by a simulation the wind power potential in the city of Triunfo in the state of Pernambuco in the northernmost region of Brazil. The study considers variation of the air density but was not included the probablistic distribution [5]. Sahin and Bilgili investigated wind characteristics in the Belen–Hatay province situated in southern Turkey for future wind power generation projects, but they did not perform a micrositting study [6]. Onat and Ersoz analyze the wind climate features of three regions in Turkey and their energy potential [7]. Celik analyzed the Çanakkale–Bozcaada region statistically. Although the title of the paper mentions Çanakkale, the study which was performed just contains the data of Bozcaada, the district of Çanakkale Province [8]. Dohmoi et al. presented an assessment of wind energy potential and optimal electricity generation in the site of Borj-Cedria in Tunisia. In Dohmoi's study, the wind speed distribution, wind power density and mean wind speed are estimated. The data collected at 10, 20, and 30 m height during 2008 and 2009 and the technical data provided by seven wind turbine manufactures have permitted to calculate the seasonal net energy production in the area [9].

For the wind power plant sitting, a number of criteria are effective including wind potential, accessibility, and the distance to the energy transmission lines. First of all, a wind atlas is created using the meteorological measurements in order to determine the potential. Then, wind measurements are performed in suitable regions considering the wind atlas. Finally, the local wind potential is determined by also taking the region's topography into account. Turkey's high potential regions are the Aegean, Marmara, and east Mediterranean regions.

According to the Turkey Wind Atlas given in Fig. 1, which has been developed by the Turkish Electric Affairs Etude Administration, in suburban locations at 30 meters or higher elevations, the average wind speeds are 6.0–7.0 m/s at Marmara, west Black Sea, and east Mediterranean shores and 5.5–6.5 m/s in their inner territories, 5.0–6.0 m/s at west Mediterranean shores and 4.5–5.5 m/s in their inner territories, and 7.0–8.5 m/s in north west Aegean shores and 6.5–7 m/s in their inner territories Figs. 2–5 shows the capacity coefficient and wind potential of Çanakkale region respectively.

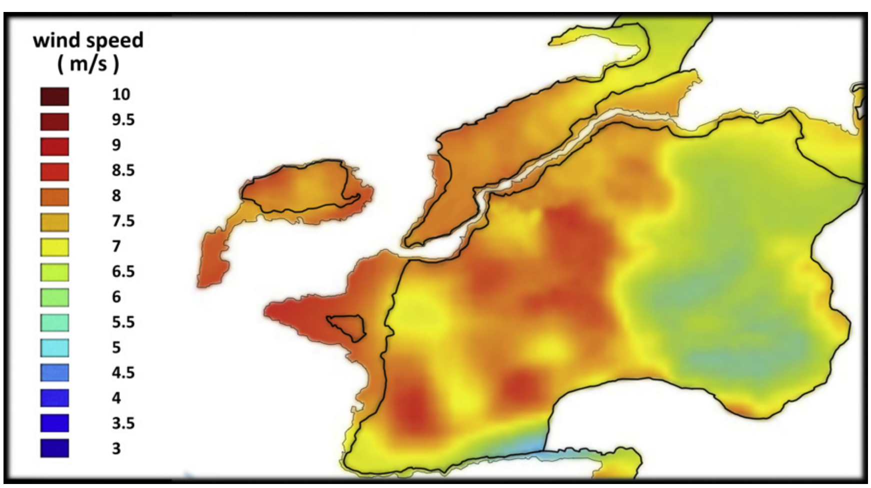

Fig. 3. Wind speed distribution at 50 m [11].

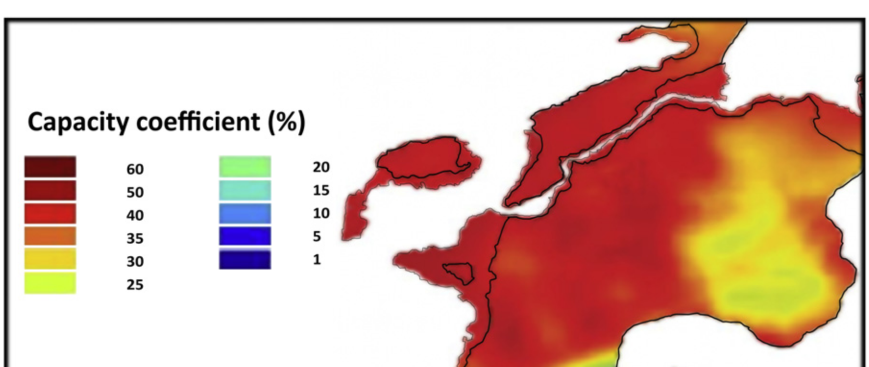

Fig. 4. Capacity coefficient—50 m [11].

For economical wind power plant investments, 35% or more capacity factor is required [12]. Considering this ratio, the above mentioned regions are suitable for wind energy investments. As seen in the wind maps given in the figure, Turkey is an appropriate location in terms of wind energy. The below given information for European countries also support this assertion.

The values of technical wind energy potential of European countries are given in Table 2. As shown in the table, Turkey has the highest share in technical wind energy potential in Europe [10].

In this study, wind farm sitting is performed for Turkey, Çanakkale—Intepe region which is suitable for wind energy potential. The wind information of the Çanakkale region is given below.

These maps developed by REPA show the high potential of wind energy in Çanakkale. REPA is the "Wind Energy Potential Atlas" in which a medium-scale numerical weather forecast model and a micro-scale wind blow model have been employed.

2. Methodology, measurements and used software for this study

2.1. WAsP software

One of the commonly used softwares in wind energy potential determination is WAsP (Wind Atlas Analysis and Application Program) which was developed in Denmark National RISO Laboratory and used in the development of European wind atlas. WAsP has been used in 100 different countries and by more than 1600 people. The software takes the effects of different roughness, curtaining effects of nearby building and obstacle effects, and the wind speed variations due to the topographic conditions into account [13]. Therefore, the modified fundamental meteorological details can be implemented through the software for better wind turbine deployment. A local position and surface statistics at a certain elevation can be exposed by the wind atlas. Moreover, the extrapolation of the average wind statistics can be investigated according to the statistical and micro-meteorological technique with regard to the wind energy evaluations.

This process helps acquire the correct information for the wind turbine sitting and estimate the wind climate for the wind energy applications.

The purposes of the WAsP are analyzing the row data, developing the wind atlas, wind climate evaluation, and estimation of the wind power potential. Row data analysis collects the row data in the histogram and provides the time series of the wind measurements. Meanwhile, the Weibull parameters are calculated using this data analysis.

In order to prepare the wind atlas data, wind speed histograms can be converted to the wind atlas data arrays. For the wind climate evaluation, wind atlas data arrays calculated through the WAsP or another source can be used for a specific local position. Again using WAsP, the estimation of the wind energy potential can be extracted through the total energy content of the average wind. In addition, the annual average energy generation of a wind turbine can be obtained using the power curve of that turbine in the WAsP. WAsP assumes that the wind speed data fit the two-parameter Weibull distribution when dealing with the data analysis. Moreover, WAsP calculates the local wind atlas statistics using four different information inputs. These four information inputs are hourly wind speed data, local roughness data, curtaining effects, and the topography of the region. WAsP uses three sub-models for processing those four inputs. These are the roughness variation mode, obstacle curtaining model, and the topographic model.

2.2. Wind data measurements and uncertainties

The important parameters and concepts of instrumentation and measurement systems can be divided into three sections,

Table 2
Wind energy potential of European countries [10].

Country	Total Area × 10^3 km^2	Technical potential	
		GW	TW/year
Austria	84	2	3
Belgium	31	2	5
Denmark	43	14	29
Finland	337	4	7
France	547	42	85
Germany	357	12	24
United Kingdom	244	57	114
Greece	132	22	44
Ireland	70	22	44
Italy	301	35	69
Luxembourg	3	0	0
Norway	324	38	76
Portugal	92	7	15
Spain	505	43	86
Turkey	781	83	166

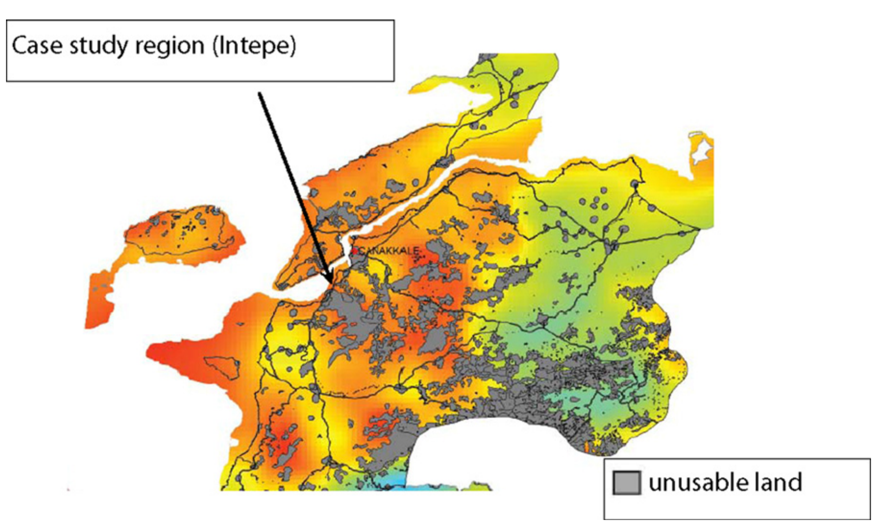

Fig. 5. Unusable fields for wind farm in Çanakkale [11].

system components, instrument characteristics and characterization of measurements.

The wind observation station, which is situated 179 m high above the sea level, stands as a mast on which an equipment is fixed that is applied to measure the wind speed and wind direction at the height of 10 m. Ammonit Wicom-32 computer datalogger is used for storing the wind speed and the direction information, and thermometer, barometer, hygrometer, and cables and terminals are used to provide the connection while 12 V/15 W solar cell is used for energy requirement. The Ammonit anemometer, which has been selected due to its simple design and easy use with its technical features being given in Table 3, and the equipment for calibration of the direction control have been provided by DEWI Institute Germany. Detailed analysis of the wind speed profile characteristics is crucial for accurately assessing the power output of a wind farm.

Wind measurements are generally performed below the wind turbine hub height owing to the higher measurement and tower cost. Since wind speed is extrapolated to the hub height of wind turbine, some critical errors may occur. Respective uncertainties are associated with measurement accuracy: the impacts of different monitoring periods; the relationships between site data and long-term reference data; methods of assessing the consistency of long-term reference data; and uncertainty in wind shear exponents. Various methods exist in the literature concerning the extrapolation of wind speed to the hub height of wind turbine. Among these methods, the Wind Power Law is the most widely used method. The Wind Power Law can be given as

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \quad (1)$$

where v_1 and v_2 are the measured wind speed at the heights h_1 and h_2 respectively. α is the wind shear coefficient. The wind shear coefficient can be determined if wind speed measurement at two heights is available and can be determined by the following equation [8].

$$\alpha = \frac{\ln(v_2/v_1)}{\ln(h_2/h_1)} \quad (2)$$

Combining expressions (1) and (2) results in the following expression for v as a function of known parameters:

$$v = v_2 \left(\frac{h_3}{h_2}\right)^{\alpha = \ln(v_2/v_1)/\ln(h_2/h_1)} \quad (3)$$

Random error of wind speed v at the hub height for uncorrelated and normally distributed uncertainties of input parameters can be expressed as

$$\Delta v = \sqrt{\sum_{i=1}^{j} (G_i \Delta x_i)^2} \quad (4)$$

where the coefficients G_i are known as the sensitivity coefficients and expressed as follows:

$$G_i = \frac{\partial f}{\partial X_i}\Big|_{X_i = v_1, v_2, h_1, h_2} \quad (5)$$

and ΔX_i are the measurement errors of input parameters. Major sources of uncertainty for wind speeds extrapolated to hub height are the respective uncertainties in the measured wind speeds v_1 and v_2; uncertainties in h_1 and h_2 have smaller impact and therefore are neglected. The total uncertainty of wind speed v at the hub height is calculated from the partial derivatives of Eq. (3) with respect to v_1 and v_2 and the corresponding measurement errors. Fig. 6 shows the monthly variation of wind shear coefficient which is considered in the calculation of the wind speed values in this study.

2.3. Methodology

In this study, the data measured from a meteorological station between 2009 and 2010 have been used. During the current investigation, the information for the speed and the direction of the wind has been collected for 24 months, making use of anemometers placed at 10 m height. The data logger recorded the parameters measured at the observation station for each second, and the average, minimum, and maximum values and their standard deviations have been measured at 10 min intervals. The field data have been transferred to a laptop computer for analysis. The recorded wind speed and direction data have been archived in the CALLaLOG software as daily files and monthly folders. The data are sampled with 10 min intervals at 10 m elevated surfaces which contain the wind direction, and the speed information was cleaned up by eliminating the incorrect and meaningless samples; i.e., negative wind speed data. The wind speed and wind direction data of 2009–2010 with 10 min intervals recorded at 10 m elevation have been edited using Editplus software and the OWC which gives the wind rise and the Weibull distribution has been developed in WAsP. Then, using the edited data and the maps, an average energy density map has been developed. For preparing the map, the orographic, roughness, and wind data of the region are processed through the WAsP Map Editor of the WAsP 8.0 software. Then, ‘‘Resource Grid File’’ which is a module of this software is used to calculate the wind intensity and the power density for the current topography of the selected region [12]. The results of these calculations are used as regional distributions of the average wind and the power density.

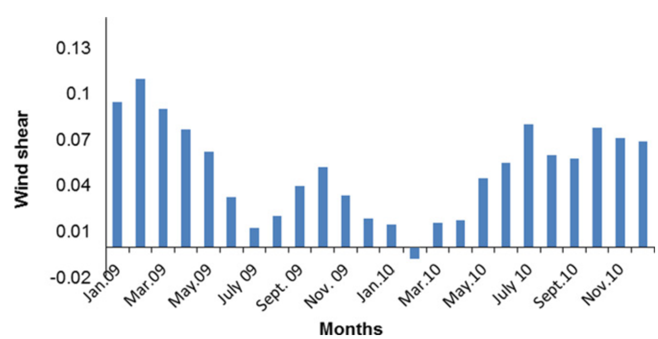

Fig. 6. Monthly variation of wind shear coefficient α for wind speed values measured at heights between 10 m and 30 m.

Table 3
Nominal specifications of equipments.

Specification	Anemometer	Wind vane	Thermometer	Hygrometer barometer	Barometer
Measurement range	0.3–50 m/s	0°–360°	−35° to 80 °C	0–100% RH	800–1600 h Pa
Accuracy	±2%	±2%	±1 °C	±1 RH	
Starting threshold	≤1.0 m/s	≤1.0 m/s	N/A	N/A	N/A
Resolution	≤0.05 m/s	1°	0.1 °C	1%	1 h Pa

2.4. Weibull and Rayleigh wind speed statistics

In order to describe the wind speed frequency distribution, there are several probability density functions. The probability density functions point out the frequency distribution of wind speed, and which is the interspace of the most frequent wind speed, and how long a wind turbine is out and on of action. The Weibull and the Rayleigh functions are the two most known functions [14–16]. The Weibull distribution is a special case of generalized gamma distribution, while the Rayleigh distribution is a subset of the Weibull. The Weibull is a two parameter distribution while the Rayleigh has only one parameter and this makes the Weibull somewhat more versatile and the Rayleigh somewhat simpler to use. The Weibull distribution function is expressed as follows where v is the wind speed, c the Weibull scale parameter in m/s, and k the dimensionless Weibull shape parameter. These parameters can be determined by the mean wind speed-standard deviation method [15–19] using Eqs. 7 and 8.

$$f_w(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (6)$$

$$k = \left(\frac{\sigma}{\overline{v}}\right)^{-1.086} 1 \le k \le 10 \quad (7)$$

$$c = \frac{\overline{v}}{\Gamma(1+(1/k))} \quad (8)$$

where v is the mean wind speed and σ is the standard deviation. $\overline{v}$ is calculated using Eq. 9 and σ using Eq. 10.

$$\overline{v} = \frac{1}{n}\left(\sum_{i=1}^{n} v_i\right) \quad (9)$$

$$\sigma = \left[\frac{1}{n-1}\sum_{i=1}^{n}(v_i - \overline{v})^2\right]^{0.5} \quad (10)$$

where n is the number of hours in the period of the time considered such as month, season or year. The dimensionless shape parameter, k, of Weibull distribution is assumed as 2 in Rayleigh distribution functions [19]. The probability density function of the Rayleigh distribution is expressed as

$$f_R(v) = \frac{\pi v}{2\overline{v}^2}\exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{\overline{v}}\right)^2\right] \quad (11)$$

The wind power density of any windy site per unit area based on any probability density function to estimate the wind power can be expressed as

$$P_m = \frac{1}{2}\rho\int_0^{\infty} v^3 f(v)dv \quad (12)$$

where ρ is the standard air density, 1.225 kg/m^3 [15,17,21]. Assuming that there is no variation in air density [20,22]. When the Weibull function is chosen as distribution function $f(v)$, the average wind power density is calculated as

$$P_{mw} = \frac{1}{2}\rho\overline{v}^3\frac{\Gamma(1+3/k)}{[\Gamma(1+1/k)]^3} \quad (13)$$

Table 4
Analysis of Çanakkale wind data with WAsP program at 10 meters in 2009–2010.

	Unit	Measured	Weibull-fit	Difference
Mean wind speed	m/s	4.26	4.23	0.03
Mean power density	W/m^2	115.2	115	0.02

3. Analysis

In the present study, hourly time-series wind data belonging to Çanakkale–İntepe have been analyzed. The mean and its standard deviation can be calculated using the time-series wind speed data by Eqs. (9) and (10). The wind speed data in time-series format are usually arranged in the frequency distribution format since it is more convenient for a statistical analysis. The annual probability density and cumulative frequency distributions obtained from the time-series data are calculated from Eqs. (11) and (12). The probability distributions and the functions representing them mathematically are the main tools which are to be used in the wind energy analysis software [8].

As seen in Table 4, the average wind speed in 2009–2010 period is recorded as 4.26 m/s and the average wind speed obtained through the Weibull curve fitting is 4.23 m/s. The deviation between the actual and fitted value is found to be 3%. Similarly, the actual power density is 114.8 W/m^2 whereas the power density through the Weibull curve fitting resulted in 115.2 W/m^2. The deviation for the power density is found to be 2%.

Wind data which were observed over a period of almost two years gathered between the years 2009 and 2010 were clustered in 12 directional sectors each one extended over 30 degree according to the direction from which the wind blows.

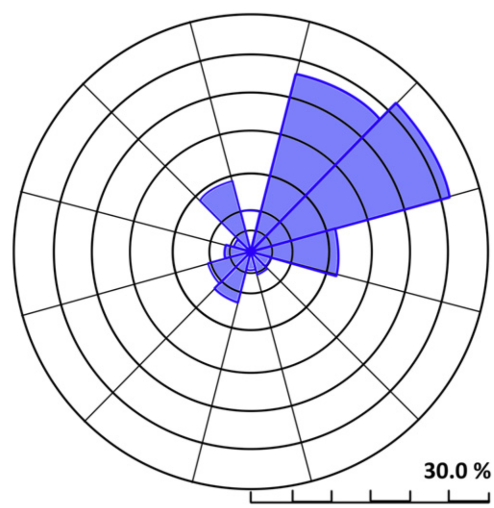

Fig. 7. Wind rise.

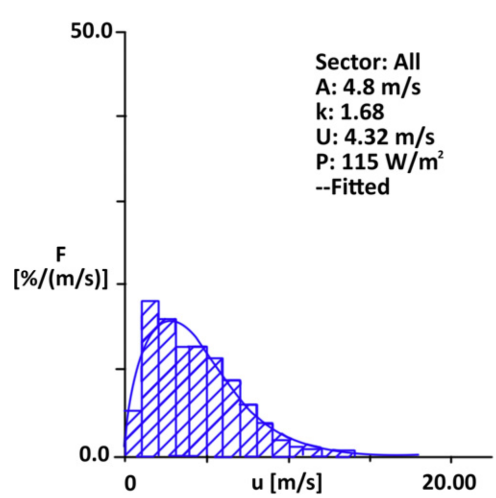

Fig. 8. Weibull distribution.

Table 5
Average wind speed, scale parameter, figure parameters, energy density, and frequency values with respect to the wind directions.

	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	All
A	4.9	4.5	5.0	2.8	1.8	7.2	7.9	7.2	6.2	5.7	3.1	4.4	4.8
k	2.33	1.90	2.36	1.16	0.79	1.67	2.38	1.93	1.85	1.81	1.40	1.91	1.68
U	4.34	3.97	4.39	2.63	2.06	6.42	6.98	6.37	5.51	5.05	2.85	3.87	4.32
E	83	77	85	48	63	380	341	314	213	168	43	71	115
f	5.1	23.5	26.1	10.9	2.2	2.6	2.3	6.4	5.6	3.4	2.5	9.3	100

Table 6
Regional wind climate according to roughness classes.

Height	Parameter	R-class 0 (0.00 m)	R-class 1(0.03 m)	R-class 2 (0.10 m)	R-class 3 (0.40 m)
10.0 m	Weibull A [m/s]	8.2	5.7	4.9	3.8
	Weibull k	1.78	1.59	1.60	1.60
	Mean speed [m/s]	7.26	5.07	4.41	3.45
	Power density [W/m^2]	510	199	131	62
25.0 m	Weibull A [m/s]	8.9	6.7	6.1	5.1
	Weibull k	1.81	1.67	1.67	1.67
	Mean speed [m/s]	7.93	6.02	5.41	4.52
	Power density [W/m^2]	651	314	227	133
50.0 m	Weibull A [m/s]	9.6	7.8	7.1	6.1
	Weibull k	1.85	1.79	1.78	1.76
	Mean speed [m/s]	8.49	6.90	6.29	5.42
	Power density [W/m^2]	780	431	329	215
100.0 m	Weibull A [m/s]	10.3	9.1	8.3	7.3
	Weibull k	1.84	1.94	1.94	1.92
	Mean speed [m/s]	9.16	8.05	7.39	6.48
	Power density [W/m^2]	980	628	488	332
200.0 m	Weibull A [m/s]	11.3	11.0	10.1	8.8
	Weibull k	1.82	1.98	1.98	1.97
	Mean speed [m/s]	10.02	9.75	8.93	7.80
	Power density [W/m^2]	1300	1095	840	563

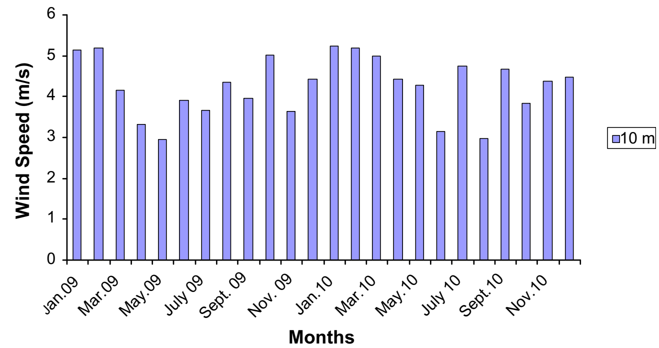

Fig. 9. Monthly wind speed at 10 m.

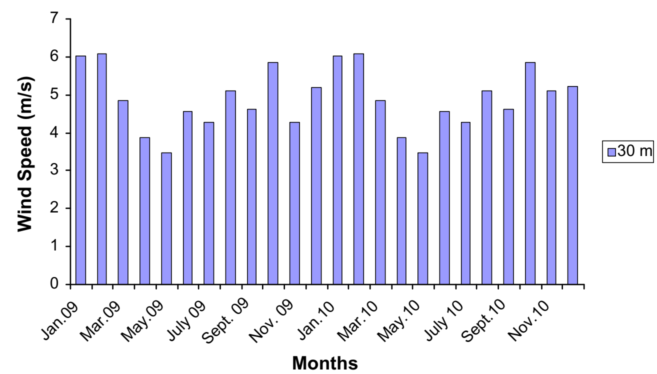

Fig. 10. Monthly wind speed at 30 m.

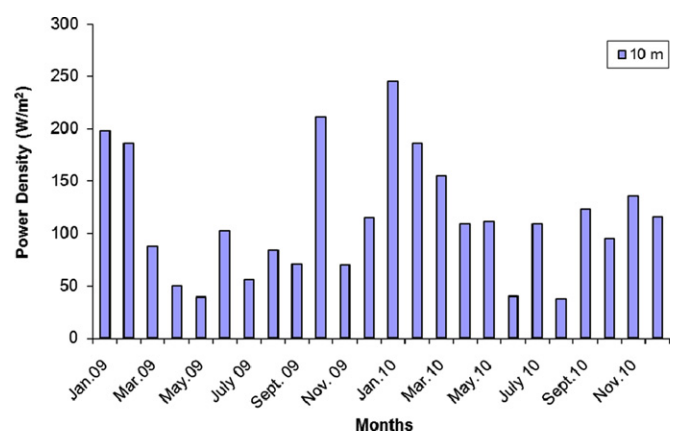

Fig. 11. Average power density at 10 m.

The wind rise provides information about the occurrence of number of hours during which wind remained in a certain wind speed in a particular wind direction [23]. The direction of wind is an important factor for establishing the wind energy conversion system [24]. If the major share of the wind from a certain direction is received, any obstructions to the wind flow from this side should be avoided. The distribution of the mean wind directions in Intepe which are marginal site is shown in Fig. 7.

Fig. 7 shows the wind rise obtained according to the measured data in the region. The dominating wind direction in the region is between 22.5° and 37.5° degrees corresponding to the NNE, NE, and SSW directions. Fig. 8 illustrates the Weibull distribution. As observed from the figure, scale parameter (A) is 4.8 m/s and the figure parameter (k) is 1.68. Table 5 shows the scale parameter, figure parameter, average wind intensity, power density, and the frequency according to the directions. Based on the table, figure parameter's maximum value is 2.38 and its direction is 180° whereas its minimum value is 0.79 and the direction is 120°. The maximum value of the average wind speed is 6.98 m/s and its direction is 180° whereas its minimum value is 2.06 m/s and its direction is 120°. The maximum value of the average power density is 150 W/m^2 at 380° and its minimum value is 43 W/m^2 at 300°. The maximum value of the frequency is 26.1 at 60° while the minimum value of the frequency is 2.2 at 120°.

Wind data which were observed over a period of almost two years gathered between the years 2009 and 2010 were clustered in 12 directional sectors each one extended over 30° according to the direction from which the wind blows.

By using the data in the frequency distribution table frequency histogram (wind speed versus frequency of blowing) and the direction histogram (wind blowing direction versus frequency of blowing) can be obtained [25].

According to Table 6, average power density and the wind speed values increase as the elevation increases. In accordance with the Intepe data, the annual maximum wind speed of the region is found to be 19 m/s in SSW direction in 2009. And the average wind speed is 4.26 m/s. Maximum power density is 419.42 W/m^2, and average power density is 115.5 W/m^2. It is observed that the Weibull parameters obtained through the WAsP equal the measured values.

Fig. 9 demonstrates the monthly wind speed values at 10 m elevation. According to this figure, the maximum average wind speed occurred in January and March months of the year 2010.

In Fig. 10, monthly wind speed is shown for 30 m elevation. This figure reveals that the maximum average wind speed blew in February 2009 and February 2010.

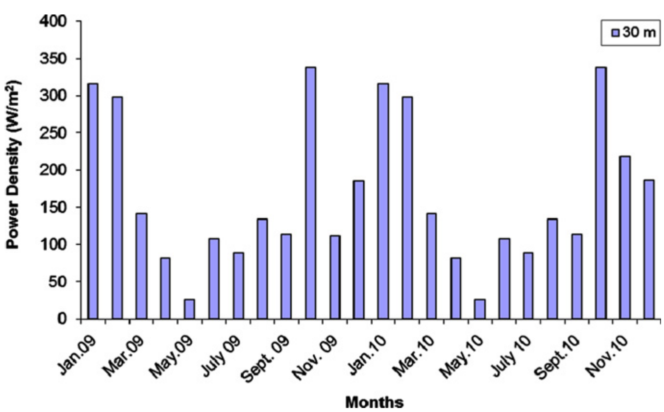

Fig. 12. Average power density at 30 m.

Table 7
Seasonal variations of average wind speed and power density at 10 m elevation.

Season	Wind speed For 10 m	Power density for 10 m
2009 Fall	3.97	68.63
2009 Winter	3.97	38.47
2009 Spring	3.60	64.25
2009 Summer	4.00	93.42
2010 Fall	4.28	114.81
2010 Winter	4.14	43.66
2010 Spring	4.57	125.29
2010 Summer	1.10	0.89

Table 8
Seasonal variations of average wind speed and power density at 30 m elevation.

Season	Wind speed for 30 m	Power density for 30 m
2009 Fall	5.07	58.23
2009 Winter	5.76	117.06
2009 Spring	3.75	51.15
2009 Summer	4.68	52.45
2010 Fall	4.78	184.53
2010 Winter	5.77	117.86
2010 Spring	5.09	176.88
2010 Summer	1.81	9.72

Average power density graphs for both of the elevations are presented in Figs. 11 and 12. The maximum power density at 10 m elevation was recorded in January 2010 whereas it was recorded in October 2009 for 30 m elevation.

The seasonal variations of the wind speed and power density for 10 m elevation are given in Table 7. According to the table, the maximum average wind speed and the minimum average wind speed values are recorded in spring and summer months, respectively. The seasonal variations of the wind speed and power density for 30 m elevation are provided in Table 8.

According to the table's data, it can be seen that the maximum average wind speed is recorded in spring and the minimum average wind speed is recorded in summer months. However,

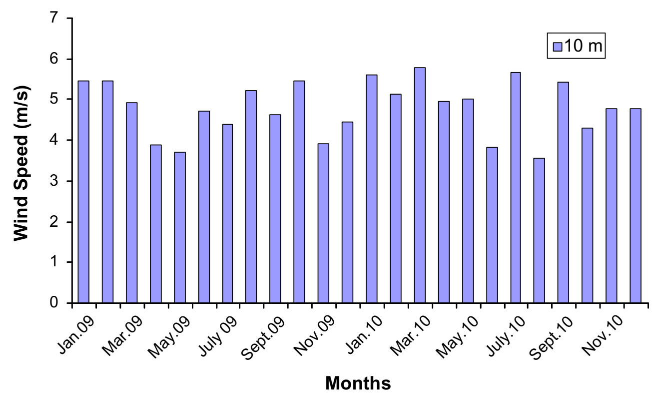

Fig. 13. Monthly wind speed at 10 m for light hours.

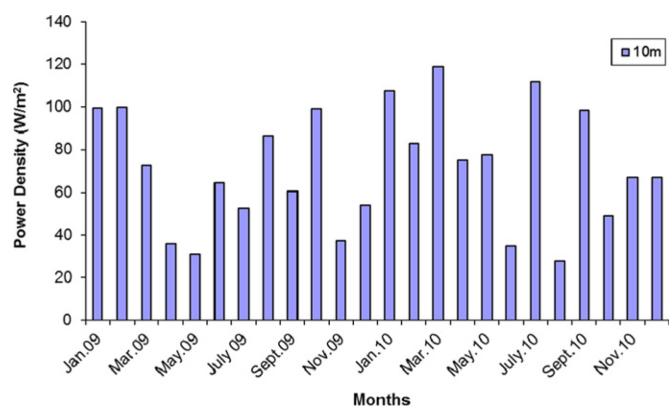

Fig. 14. Monthly power density at 10 m for light hours.

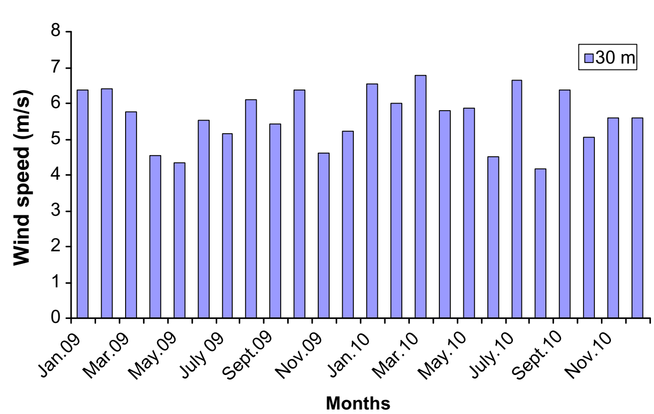

Fig. 15. Monthly wind speed at 30 m for light hours.

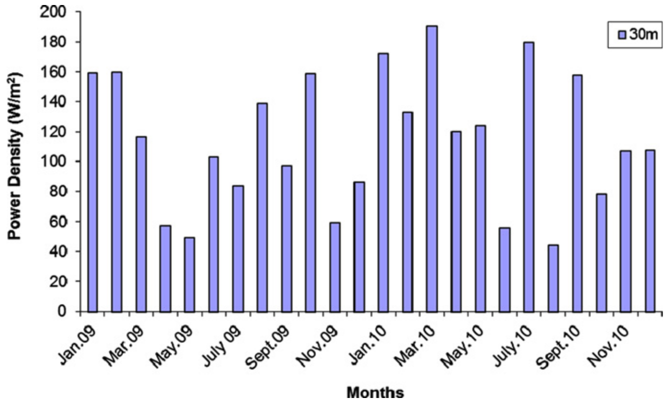

Fig. 16. Monthly power density at 30 m for light hours.

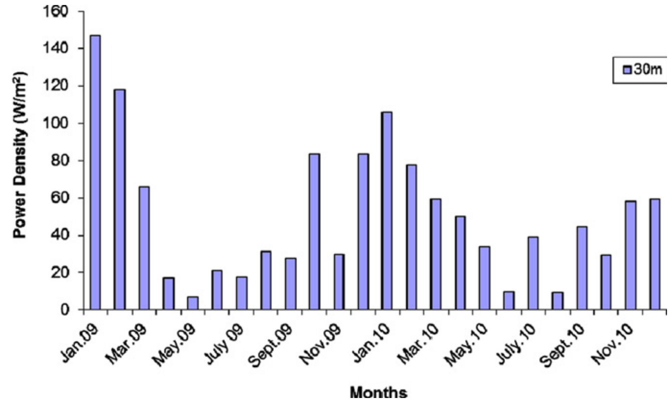

Fig. 20. Monthly power density at 30 m for night hours.

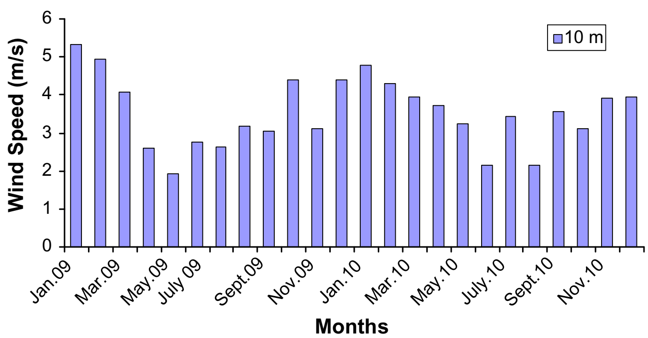

Fig. 17. Monthly wind speed at 10 m for night hours.

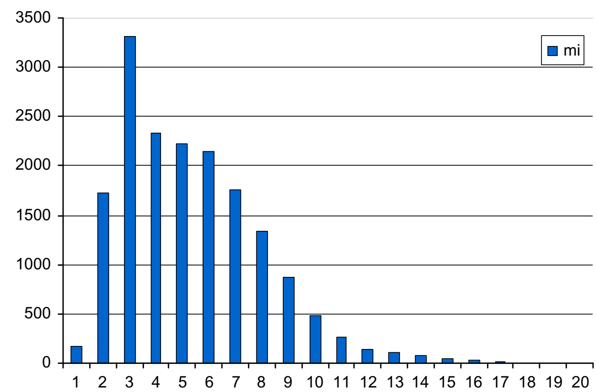

Fig. 21. Wind speed distribution depending on m_i.

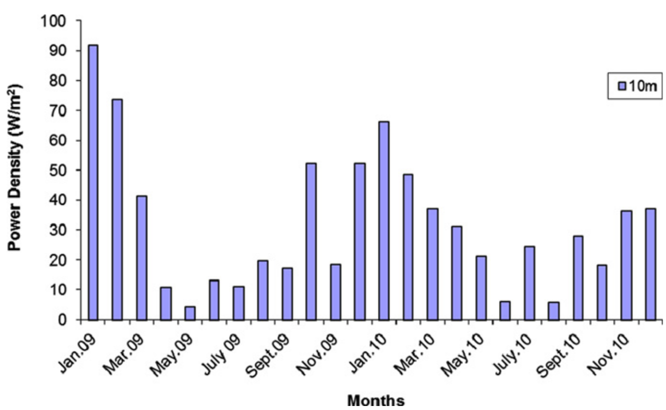

Fig. 18. Monthly power density at 10 m for night hours.

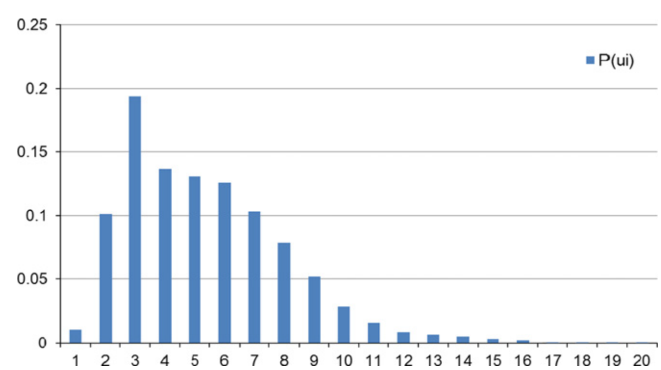

Fig. 22. Probabilistic distribution histogram.

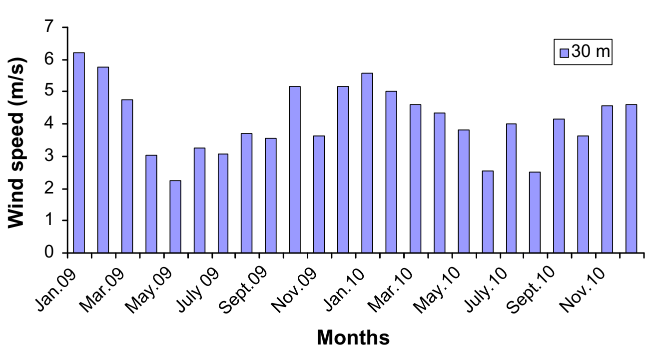

Fig. 19. Monthly wind speed at 30 m for night hours.

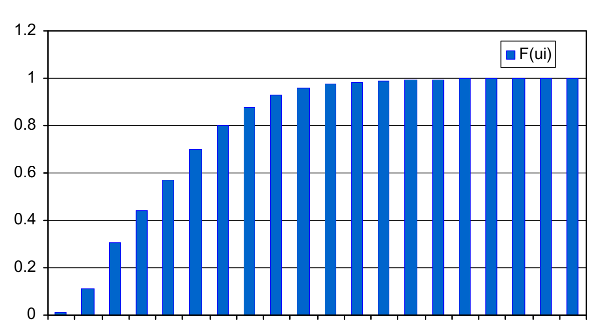

Fig. 23. Cumulative density histogram.

maximum power density variations can only be observed in winter.

Monthly wind speed and power density analyses for light hours are provided in Figs. 13–16. Monthly wind speed and power density analysis for night hours are provided in Figs. 17–20.

3.1. Data frequency analysis

In order to estimate the wind energy potential, turbine operating characteristics, and the annual energy generation, wind statistics are required [26]. The probability of each independent variable can be calculated by

$$P(u_i) = \frac{m_i}{N} \tag{14}$$

According to the data sets of the region, N value is found to be 17,100. Therefore, the speed graph depending on the m_i value is presented in Fig. 21. The sum of all of the probabilities always equals 1.

Probabilistic distribution histogram and the cumulative density histograms are shown in Figs. 22 and 23 respectively.

3.2. Persistence calculations

The persistence values of the Intepe region are calculated by using four different methods. These methods are the Lambert method, speed continuation curve, Weibull function, and the log-normal methods [27]. The persistence value is calculated to be 0.058 based on the Lambert method. The distribution curves according to the other methods are given in Figs. 24 and 25.

According to the probability density functions, the interspace has the most frequent wind speed, and so an estimate of how long a wind turbine is out and on of action can be assessed. As it is shown in Fig. 7, the distribution of wind speed of Intepe is wide. It means that its interspace which has the most frequent wind speed is high and comprises other wind speed values.

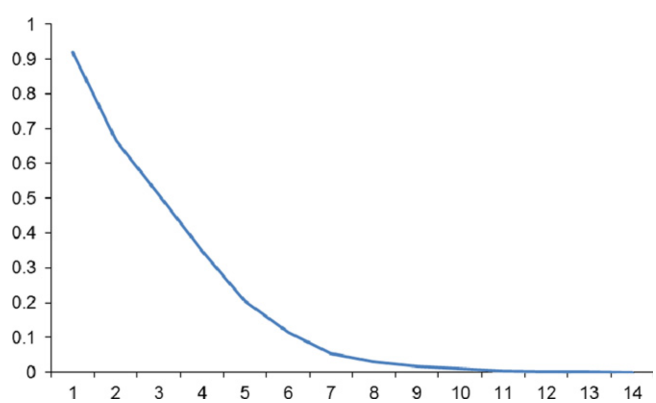

Fig. 24. Wind speed versus persistence (p/t_i).

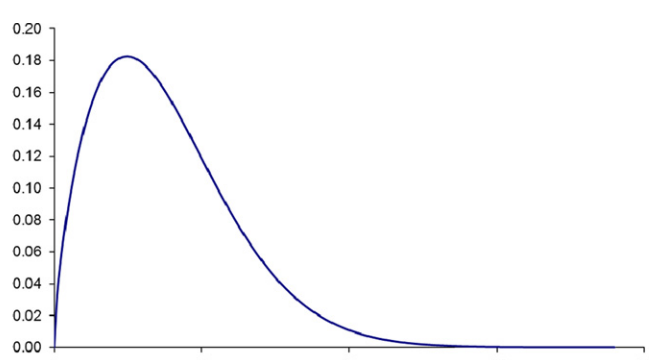

Fig. 25. Weibull distribution curve (p/v).

3.3. Weibull, Rayleigh and normal distribution

The observed wind speed frequencies are compared with the Weibull, Rayleigh, and normal distribution functions. Fig. 26 shows the comparisons of each distribution based on the methods. Table 9 and Table 10 presents the values that are used for these distributions.

The Weibull and the Rayleigh distributions resulted in obtaining very close values; on the other hand, normal distribution showed extreme values along the average wind speed. However, when the measured values are compared with the distribution values, it is seen that the Weibull distribution best suits the actual values. The sector values of k vary over a narrow range, where estimation of k depends mainly on the measured values of mean monthly wind speed. This confirms the stability of atmosphere throughout the year over Intepe region.

4. Wind energy yield estimation results

With the aid of the frequency histogram, which wind speed values are the most frequent can be observed. On the other hand, direction histogram can be used to determine in which directions the wind blows fastest [28]. As shown in Fig. 27, the analysis software is used to locate the turbine to the most appropriate coordination in this study. Digital map showing wind turbines locations is given in Fig. 27.

First of all, the Bonus Mk IIIC 600 kW turbines are placed at the locations that have the best power density in the maps. The hub height of the turbine is taken to be 50 m. The positions of the turbines on the map are shown in Fig. 27. The technical parameters of the Bonus Mk IIIC turbine are given in Table 11. It should be noted that the turbines are placed in parallel to the dominating wind directions while avoiding the wake effect. The minimum distance between each turbine should be at least 7D in accordance with the general assumptions.

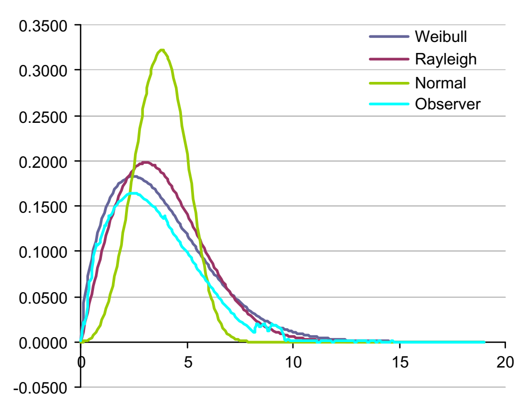

Fig. 26. Distribution functions.

Table 9
Values used for the Weibull, Rayleigh, and Normal distributions.

	$n^n e^{-n}\sqrt{2\pi n}$	$\Gamma(n+1)$	n	Standard deviation	Average	k	c
w	0.873	1.003	0.598	2.658	4.265	1.671	4.252
r	0.832	0.982	0.500	2.658	4.265	2.000	4.344
n	0.737	0.991	0.278	2.658	4.265	3.600	4.303

Table 10
Sectoral wind speed frequencies, Weibull parameters, power density and speed discrepancy.

Sector number	Sector angle [°]	frequency [%]	Weibull-A	Weibull-k	Mean speed [m/s]	Power density [W/m^2]	Speed discrepancy [%]
1	0	5.1	4.9	2.33	4.34	83	2.91%
2	30	23.5	4.5	1.90	3.97	77	0.40%
3	60	26.1	5.0	2.36	4.39	85	1.95%
4	90	10.9	2.8	1.16	2.63	48	−11.58%
5	120	2.2	1.8	0.79	2.06	63	−16.25%
6	150	2.6	7.2	1.67	6.42	380	1.78%
7	180	2.3	7.9	2.38	6.98	341	3.81%
8	210	6.4	7.2	1.93	6.37	314	3.59%
9	240	5.6	6.2	1.85	5.51	213	2.54%
10	270	3.4	5.7	1.81	5.05	168	3.32%
11	300	2.5	3.1	1.40	2.85	43	−4.71%
12	330	9.3	4.4	1.91	3.87	71	1.51%

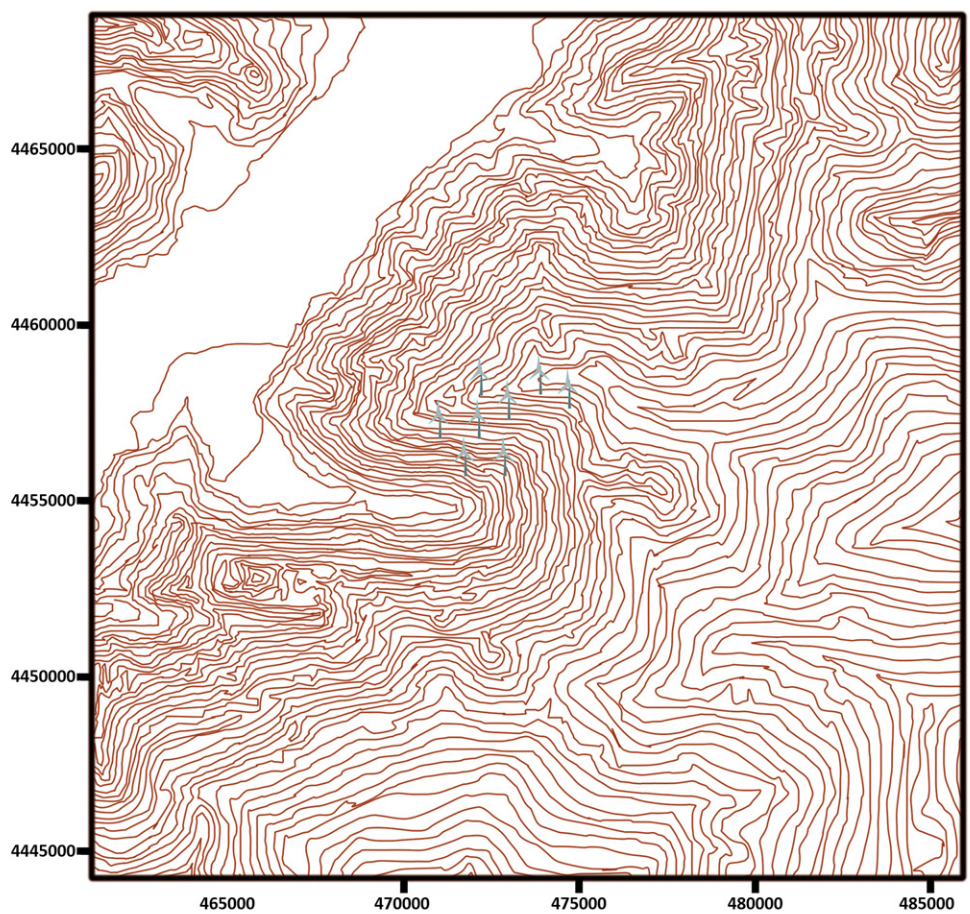

Fig. 27. Map for wind turbine locations in Intepe region.

Table 11
Estimated turbine locations and annual energy production and wake loss data for suitable turbine type.

Site	Location [m]	Turbine type	Elevation [m a.s.l.]	Height [m a.g.l.]	Net AEP [GWh]	Wake loss [%]
Turbine 001	(472879.0, 4455951.0)	Bonus 600 kW Mk IIIC	144	50	1.529	0.41
Turbine 002	(471758.4, 4455881.0)	Bonus 600 kW Mk IIIC	185	50	1.853	0.62
Turbine 003	(472213.6, 4457037.0)	Bonus 600 kW Mk IIIC	190	50	1.499	0.6
Turbine 004	(473019.1, 4457632.0)	Bonus 600 kW Mk IIIC	166	50	1.359	0.42
Turbine 005	(473929.6, 4458262.0)	Bonus 600 kW Mk IIIC	287	50	1.761	0.12
Turbine 006	(474770.1, 4457737.0)	Bonus 600 kW Mk IIIC	232	50	1.510	0.09
Turbine 007	(471058.0, 4457002.0)	Bonus 600 kW Mk IIIC	283	50	1.822	0.39
Turbine 008	(472213.6, 4458227.0)	Bonus 600 kW Mk IIIC	270	50	1.508	0.14

5. Conclusions

It is known that today's conventional energy generation and consumption technologies have adverse effects on the environmental and natural resources at local, regional, and global levels. Therefore, the idea of the generation and consumption of the energy without harming the environment has gained attention. Countries speeded up the developments of reliable, economical, and high quality energy generation technologies along with the free market mechanisms, particularly the renewable energy sources with near-zero emissions. Renewable energies such as wind energy may not be the sole solution due to their variable characteristics.

However, these energy sources are attractive since they provide the diversification of the energy sources. The fact is giving the priority to the local resources and making the use of the wind energy technologies to Turkey's economy. Consequently, the determination of the wind energy potential and the appropriate wind resource regions for investments is required.

The aim of this work is only a preliminary study in order to access wind energy analysis in Intepe and give useful insight to engineers and experts dealing with energy. The technical and economic potential was estimated to quantify the conditions of the case study region regarding the utilization of the wind source.

In this study, the mean wind speed and energy density were measured at Intepe for 24 months between 2009 and 2010 by the WAsP software. The WAsP software results for 10 m, 30 m and 100 m show that wind energy potential of Intepe is considerably high. Wind speed values show evident variation over the year. This is due to the geographical properties of the region. The mean wind speed values are over 5 m/s according to wind analysis and this region has certain wind direction as well. So, the area is suitable for a wind farm.

In order to complete the analysis of speed it is essential to know the persistence properties. So as to quantify the wind speed persistence in different sites of a determined region, four different methods have been used. These methods are the Lambert method, speed continuation curve, Weibull function, and the log-normal methods. These methods have been applied to hourly data of wind speed in the Intepe during the years 2009–2010. As a result of this analytical approach, the series of persistence validates the results obtained.

The analysis software is used to locate the turbine to the most appropriate coordination in this study. And suitability and availability for these applications are acceptable in terms of other aspects such as being in close proximity to the electrical grid lines, land ownership, road network infrastructure. Since there is a seaport in Çanakkale, the equipments required for the wind turbines can be transported easily via seaway. The wind turbine can be located in appropriate coordinates because of the analysis which is presented in this study.

Acknowledgments

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